Dispersing Oil Spills in the Straits: Assessing Fisheries and Ecological Tradeoffs

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Introduction

Chemical dispersion has been a hotly debated, but rarely used, method for combating oil spills. During the past 30 years, mechanical containment and recovery and shoreline cleanup, coupled with extensive bird and wildlife rehabilitation, have been the primary responses to spills in the Pacific Northwest. There is now renewed interest in using dispersion as a rapid-response tool to reduce oiling and injuries to wildlife and shorelines.

Dispersants are most effective when used early in a spill. Use of chemical dispersants is currently permitted only on a case-by-case basis in Washington and Oregon, and only offshore. Approval requires consultation with resource agencies at the time of a spill. Pre-approval would greatly reduce this decision lag-time and help ensure that dispersion capability is available locally. Further, since most spills begin nearshore, there is interest in pre-approval, or at least quick approval, for dispersing spills in shallow water.

During the past three years, Ecological Risk Assessment (ERA) workshops took place in Washington, Texas, and California to acquaint resource managers with current information about dispersing oil and to support pre-approval, quick approval, and/or shallow water approval processes. The National Oceanic and Atmospheric Administration (NOAA) supported these workshops with oil spill simulations and other technical contributions. This paper briefly summarizes current knowledge about dispersants and dispersing oil and then reviews the methods we used to simulate dispersed and non-dispersed spills in the Straits of Juan de Fuca, the resulting trajectories and fates, and how the scenarios were used in ecological risk assessments.

Background

Dispersants and Dispersion

Dispersants are chemicals that break up oil slicks. Current formulations, such as Corexit 9500® and Corexit 9527®, contain surfactants and solvents that reduce the surface tension of floating oil (NRC, 1989; S.L. Ross, 1997). During dispersant operations, neat or diluted mixtures of dispersants are loaded onto aircraft or boats and sprayed as a fine mist directly on the oil slicks. The dispersant mixture breaks up the oil into tiny (10- to 100-micron) droplets. With adequate wave energy, such as a light wind chop, the oil droplets mix down into the water column and spread laterally, resulting in turbid "clouds" or plumes of oil located within a few meters of the sea surface. Over the next few minutes and hours these plumes continue to spread, dilute, mix downward, and move out of the spill area with prevailing currents.

By breaking up and submerging oil, treatment of oil slicks with dispersants can quickly and effectively reduce the risk of oiling of sea birds, marine mammals, and sensitive shorelines (NRC, 1989). Dispersion also increases the rate at which oil is degraded (Cretney and others 1981; Swannel and Fabien 1999) and, if used early, may help prevent the formation of water-in-oil emulsions (“chocolate mousse”) and tar balls (NRC 1989). Other response actions, such as skimming, open-water burning, and shoreline cleanup, also remove oil and reduce wildlife injuries, but not nearly as fast, as effectively, or as completely as a dispersant operation. Moreover, all response options, including skimming, shoreline cleanup, and dispersion, can cause ecological injuries above and beyond those caused by the oil itself (Table 1; Mearns 1996; API 2001). Finally, not intentionally dispersing oil does not mean that it is not dispersing: many light and medium oils disperse naturally (NRC 1989).

Table 1. Countermeasures available to marine spill responders and some of their ecological impacts. Each is effective under certain conditions but each can cause collateral effects or redistribute oil ("stressors" in risk assessment). Does not include logistical support required for response personnel. Asterisks denote actions requiring special approval. Assembled from various sources, including API (2001) and Mearns (1996).

Countermeasure (Stressor)	Ecological Impact (Stress)
No Action (natural recovery)	Low if oiling light
Open Water Response	
Containment Boom	oil in undertow water; chain rips sea grass
Skimmers	noise, air pollution
In Situ Burning*	smoke
Chemical Dispersion*	water column toxicity
Chemical Herding*	toxicity?
Shoreline Cleanup	impact eggs of shore spawners (generally)
No Action (Natural recovery)	slow; toxicity, smothering
Manual Removal	damaging foot traffic(marshes)
Mechanical Removal	physical shoreline damage
Sorbents/Passive Collection	excess waste generation
Vacuum	fuel consumption, foot traffic
Sediment Reworking/Tilling	sediment physical damage
Bern relocation	resuspension/dispersion of oil
Surf Washing	resuspension/dispersion of oil
Vegetation Cutting/Removal	stress to marsh if not careful
Burning*	
Marsh	combustion of biota; smoke
On beaches	smoke
Deluge Flooding	nearshore dispersion of oil
Ambient Temperature Washing	
Low Pressure	nearshore dispersion of oil
High Pressure	mortality to surviving biota
Warm and Hot Water Washing	mortality to surviving biota
Sand and Slurry Blasting	mortality to surviving epibiota
Chemical Countermeasures*	
Shoreline Cleaning Agents	toxicity; shoreline dispersion
Solidifiers	not enough experience
Bioremediation*	
Nutrient Enhancement	nutrient, metabolite toxicity
Bacterial Inocula	metabolite toxicity

Obviously, the benefits of intentionally enhancing dispersion of oil must be weighed against possible effects of dispersants and dispersed oil on life in the water column, including fish and fish habitat. Both dispersants and fresh oil are toxic to sensitive life stages of fishes and invertebrates, dispersants being the least toxic of the two (NRC 1989; Singer and others 1999; Clark and others 2001). Although dispersed oil does not sink to the sea floor, plumes of dispersing oil may drift over shallow-water benthic habitats such as oyster and clam beds or populations of shrimp, demersal fish or sea grasses. Depending on exposure time and oil concentrations, these organisms may become temporarily contaminated with oil or petroleum hydrocarbons (NRC 1989; Page and others 1983; Michel and Henry 1997). If dispersed oil concentrations are high enough, and exposure long enough, exposed populations may be injured or killed.

Dispersion effectiveness is limited by several constraints: (1) The oil must be dispersible (some heavy oils are not); (2) Sufficient wave energy must exist to mix dispersed oil into the water column (light chop a minimum); (3) Treatment must be done during the early hours following the spill (weathered oil is less dispersible than fresh); and (4) The operation must be logistically feasible (NRC 1989). Conventional wisdom has held that the window-of-opportunity—that is, the set of physical and temporal conditions that allows chemical dispersion to be an effective response—is narrow and generally limited to the first few hours to a day after a spill and to a modest range of fuel and oil types (NRC 1989; Reed and others 1999). Thus, the decision to disperse must be made quickly if it is to be an effective tool. Time spent debating the pros and cons is time lost.

Recent Advances

The NRC (1989) conducted a detailed review of review of dispersant use, fate, and effects. They identified a number of uncertainties, most of which have been resolved during the 1990s. The principal concerns were fate and toxicity (Aurand 1995a) and poor communication of existing knowledge (Bostrom and others 1997.) During the 1990s, several coordinated industry, government and academic field and laboratory activities were conducted to resolve issues dealing with dispersed oil fate and toxicity (Aurand 1995b; S.L. Ross 1997; Singer and others 1998; Rhoton and others 1999; Page and others 2000; George-Ares and Clark 2000; Clark and others 2001). Dispersant formulations have been refined, and there is a considerable body of new knowledge about dispersant effectiveness (Clayton and others 1993; Fiocco and others 1999b; Lunel and others 1997; S.L. Ross 1997; Lunel and Lewis 1999; and Lessard and DeMarco 2000). Through direct field trials (intentional oil spills), the conventional window-of-opportunity has been widened to accommodate heavier oils and increased response time extending toward two days (S.L. Ross 1997; Fiocco and others 1999a). Finally, there are now new data from laboratory, mesocosm, and field studies about oil dispersion processes, better numerical models, and more effective treatment operations.

Equally important is new and controversial information suggesting that small amounts of oil remaining after even extensive shoreline cleanup are sufficient to injure embryos of shore-spawning fishes such as Pacific herring (*Clupea pallasi*) and pink salmon (*Oncorhynchus gorbuscha*) (Kocan and others 1996; Carls and others 1999; Heintz and others 1999; and Marty and others 1997). Indeed, aggressive shoreline clean up itself disperses oil into very shallow water, damages surviving shoreline biota, and delays recovery of shoreline habitat (Table 1 and Mearns 1996). Thus, efforts to prevent shoreline oiling will reduce the long-term impacts of an oil spill on essential fish habitat (EFH). Although this new knowledge raises more questions it also brings into clearer focus important tradeoffs of all response options.

Current Policy

During the 1990s, dispersants were pre-approved for use in most U.S. Atlantic and Gulf of Mexico coastal waters beyond 2 or 3 nautical miles and beyond the 10- or 20-m isobath, and even closer to shore in Hawaii. Beyond these zones the U.S. Coast Guard Federal On-Scene Coordinator (FOSC) is pre-authorized to order dispersant applications without additional consultation with federal or state resource trustees. During the last three years, under pre-approval guidelines, at least four oil spills have been treated with dispersants in Louisiana and Texas (two reviewed in Gugg and others 1999.) In 2001, the Coast Guard and NOAA supported nearshore or shallow water dispersant use at wildlife-threatening spills in the Galapagos Islands and near Barbers Point in Hawaii.

Dispersant pre-approval has not been implemented for the U.S. West Coast. Dispersants are not banned in Washington or Oregon, but they cannot be used in inshore waters without deliberation and consultation on a case-by-case basis (at the time of the spill). In Washington, the pre-approval plan (Washington State Department of Ecology 1993) has not been implemented pending state approval of a monitoring plan. Once implemented, dispersant use in Washington is pre-approved when all of the following conditions are met: water depths greater than 20 m; sufficient mixing energy to rapidly dilute oil concentrations; distance from sensitive resources and nearshore sub-regions is 3 miles; there is significant likelihood that oil will impact sensitive resources; the subregion is greater than 200 km^2; and resource value (determined by a rating) of birds, marine mammals, and shorelines are higher than those for fish and shallow-water benthic communities (Ecology 1993). When implemented, this policy will permit use in offshore open coastal waters and in the central part of the Straits of Juan de Fuca west of Port Angeles, but it will also effectively preclude dispersant use in all of Puget Sound and the Straits of Juan de Fuca east of Port Angeles. In Oregon, dispersant use remains on a case-by-case basis; Oregon has accepted the Washington criteria, but has not yet applied them to a pre-approval process. There is growing interest on the part of states and the Coast Guard to pre-approve or quick-approve dispersant use in both offshore and nearshore waters, and to develop and pre-stage dispersant response capabilities.

Scenarios for Ecological Risk Assessment

To obtain approval or pre-approval, offshore or in shallow waters, the Coast Guard and the states must consult with state and federal resource trustees and the public. During 1998-2000 the Coast Guard, together with several state agencies, hosted a series of Ecological Risk Assessment (ERA) workshops (following Aurand 1995b) to evaluate and compare the benefits and risks of dispersing oil spills in nearshore and/or shallow-water areas. Work groups included resource trustee decision makers (risk managers) and resource scientists (risk assessors). NOAA supported these workshops by providing oil spill model results for site-specific scenarios and other information needed to evaluate the effectiveness and effects of spill response operations.

In Washington, risk managers decided on a worst-case scenario involving a refinery crude oil spill that threatened the San Juan Islands in April when many resource species were reproducing, nesting, fledging and migrating (Walker and others. 2001.) This scenario was especially poignant with respect to fishery tradeoffs as it occurred while fisheries agencies were implementing the Endangered Species Act listing of Puget Sound salmon, and considering listing of herring, cod, hake, pollock and three species of rockfishes: in other words, declining fishery stocks with life stages occurring on shorelines (herring) and in shallow and deep waters (all species). Agreement was reached on a hypothetical incident involving release of 22,948 L (500 bbls) of Prudhoe Bay crude oil (BC) occurring on April 11, 1998 at an oil refinery at March Point, Anacortes in Guemes Passage, an eastern inlet to the Straits of Juan de Fuca. The spill occurred at the onset of an ebb tide with 10-knot easterly winds pushing the oil slick out into Rosario Strait. At 1000 hours, six hours post-spill, the surface oil was in the eastern Strait of Juan de Fuca near Whidbey Island. At this point the winds were shifted to 10 knots from the south, causing the floating oil to move north and threatening the San Juan Islands area.

At this time (1000 hrs; daylight), the spill was dispersed. From this point forward two spills were simulated: the floating oil slicks initially moving north toward the southern San Juan Islands and the dispersed plume originating 2-3 miles off northern Whidbey Island and moving wherever currents dictated. This wind condition (10 knots from the south) was to prevail during the following 3-4 days (to 96 hours) of the spill. Participants were then challenged to evaluate and compare the ecological benefits and consequences of dispersing the oil or not doing so. The balance of this paper describes our modeling methods, the resulting trajectories and how the models were used in the risk assessment workshops.

Spill Simulation Methods

Modeling Methods

We used two existing operational models, and a simple box model, to produce oil spill spreading and trajectory maps, charts of oil fate and transformations (weathering), and dilution and transport of dispersed oil.

Oil Slick Spreading and Trajectory.

We simulated the spreading, breakup and trajectories of the oil spills using NOAA’s On-Scene Spill Model (OSSM; Torgrimson 1984). Inputs included maps, coastal outline and shoreline descriptors, bathymetry, numerical circulation models, statistical climatological simulations, location and type of the spilled substance, oceanographic and meteorological observations, and other data. Current speeds and directions were derived from tidal currents and current meter records as modified by bathymetry. The output included time series maps showing the overall size and shape of the oil slick footprint, the concentrations of oil (percent cover) within the footprint, and climatology-derived confidence limits.

Fate and Transformation.

Oil properties (density, viscosity, volume, chemical composition) are rapidly transformed by spreading, evaporation, dispersion, emulsification, dissolution, oxidation, sedimentation and biodegradation (collectively referred to as oil weathering.) For example, once released, the oil will lose mass and increase in viscosity due to evaporation and natural dispersion, and then increase in mass due to water-in-oil emulsion formation (mousse). Transformation imposes increasing constraints on response. Highly viscous oil and mousse are very difficult to disperse and may be difficult or impossible to skim without special equipment; mousse is nearly impossible to burn.

Transformations of floating oil properties were computed using Automated Data Inquiry for Oil Spills (ADIOS; Lehr and others 1992). ADIOS integrates a library of approximately 1000 oils with a short-term oil fate and cleanup model to help estimate the amount of time that spilled oil will remain in the marine environment, and to develop cleanup strategies. Input included wind speed, salinity, water temperature and wave height and type of oil. Output included time series (we chose 3- to 12-hour intervals) of means and ranges for percent evaporation, percent water, viscosity, and percent natural dispersion. From these we calculated remaining oil and mousse volumes.

Dispersion Simulation.

When dispersant is applied to floating oil, the oil is also broken into discrete particles or droplets that quickly mix down into the upper surface layer (1.5 times the wave height, Delvigne and Sweeney 1988). Most of the chemically dispersed oil droplets (less than about 60 microns) are neutrally buoyant and do not return to the surface. Langmuir circulation, caused by wind blowing on the water and setting up circulation cells (10s - 100s of meters apart) move the neutrally buoyant droplets vertically, down through the upper mixed layer, stopping at the thermocline or pycnocline (Mackay and others 1982.)

We simulated the dispersion of oil using simple, one-dimensional box modeling. The volume to be dispersed was determined by fate modeling, above, and by the ERA Workshop managers' judgment on the effectiveness of a dispersant operation. For the first hour following dispersion, this final volume was mathematically mixed vertically down to a 1.5 times the wave height (defined by wind speed.) Over the next few hours the dispersed oil was mathematically mixed down to the top of the thermocline. The spreading and trajectory of this oil-contaminated water mass was simulated using OSSM, but the wind was removed as a direct factor (the wind contribution to the current itself was retained.)

Dispersed Oil Concentrations.

Mean dispersed oil concentrations, in mg/L or parts per million (ppm) were computed simply by dividing the dispersed oil volume (in liters or gallons) by the volume of water containing the dispersed oil (that is, the product of the plume footprint area and its thickness). The calculation was performed for each of several time intervals (1, 2, 3, 4, 5, 6, 12, 18, 24, 36, 48, , 72, and 96 hours). The result was a series of mean dispersed oil concentrations that begin at a very high peak value and then decrease continuously as the contaminated water volume increases.

Uncertainty.

Several types of uncertainty were also addressed in the simulations. As noted above, uncertainty regarding the speed, spreading and transport of undispersed surface slicks were defined by seasonal climatological variability and estimated error in wind direction and speed (Galt 1997; Galt 1998). We also expect the actual concentration of dispersed oil in the water column to have a large variability around the mean that was computed. The primary reasons for this are the patchiness of the surface oil distribution at the time of dispersant application, the uneven application of the chemical dispersant, and the spatial variations of the vertical mixing functions such as wind waves, and Langmuir circulation. Based on a comparison of modeling with actual data from Southern California intentional oiling field experiments, Mackay and others (1982) urged considering a factor of 3 around estimates of dispersed oil concentrations. To accommodate for all these sources of variability and uncertainty, we computed upper and lower dispersed oil concentrations as 5 times and 0.2 times the mean. These values represent our "operational" best professional judgment based on direct observation and other modeling activities related to dispersion processes.

Assessing the Ecological Effects of Dispersed Oil

ERA Workshop participants agreed that toxicity to marine fishes and invertebrates was their primary concern about the hazards of dispersing oil. A large body of data exists concerning the acute and chronic toxicity of mechanically and chemically dispersed oil and dispersants to adult and juvenile marine organisms. These data were presented to, and examined by, resource biologists during the course of the ERA workshops. The data were then used to develop consensus toxicity guidelines to compare with the expected dispersed oil concentrations derived from the modeling.

Toxicity of Dispersants and Dispersed Oil

Most of the marine life toxicology data is based on 96-hour constant-exposure bioassays. Over this time scale (96 hours), dispersion results in constantly changing or declining concentrations following an initial peak. Fortunately, Singer and others (1998), Rhoton and others (1999), Clark and others (2001), and others have compared this type of exposure with "spike" or "pulse" bioassays that attempt to mimic what happens during a chemical dispersion episode. Results of these studies, published since the mid-1990s, generally indicate that zooplankton and early life stages of tested marine plants and animals are less sensitive to spiked exposures than to constant exposures. From a sample of these new data (Table 2, below) it is obvious that the dispersant Corexit 9500 was at least 10 times less toxic than either mechanically dispersed or chemically dispersed oils and, further, that spiked oil or dispersed oil was less toxic than 96-hour, constant-exposure oil. Therefore, in developing consensus criteria for concentrations of concern, participating risk assessors considered both short-term spike exposure data as well as the longer-term (96 h) "acute" toxicity data.

Table 2. Ranges of 96-hour constant and spike EC50s and LC50s for juvenile early life history stages of 7 species of fishes and invertebrates subjected to a dispersant (Corexit 9500), mechanically dispersed or water-accommodated fractions (WAFs) of three oils, and chemically dispersed fractions of two oils. Based on data in CROSERF, 8th report, Coelho and Aurand (1998). BC = Prudhoe Bay crude oil.

	Type of Exposure/LC50 in ppm (mg/L)	
Treatment	**Constant**	**Spiked**
Corexit 9500	30 - 150	90 - 1000
BC	3 - 15	8 - 26
BC+ C9500	1 - 8	5 - 18
Arabian	0.6 - 6	15 - 80
Arabian+ C9500	0.8 - 1.6	29 - 58
Venezuelan	0.2 - 0.4 1	
Venezuelan+ C9500	no data yet	no data yet

Consensus Guidelines

After reviewing selected papers and reviews of data on the toxicity of dispersed oils to marine invertebrates and fishes, participants in each workshop were polled to determine their *levels of concern* (i.e., discomfort levels) with a range of exposure times and water concentrations. Assessments were done separately for adult fish, adult crustaceans (shrimp, crab), and for zooplankton and/or sensitive life stages of fish and crustaceans. In all three workshops it was quickly agreed that the most sensitive forms were zooplankton and the early life stages of fishes and crustaceans. Also, the guidelines proposed independently in all three workshops were in remarkable agreement about concentrations and exposure times of concern. Our summary of these consensus guidelines is presented in Table 3

Table 3. Saltwater-dispersed oil consensus concentrations (ppm), and exposure periods (hours) of concern used in this report to evaluate potential toxicity of dispersed oil plumes to marine zooplankton and early life history stages of fishes and invertebrates, adult crustaceans, and adult fishes. Based on consensus guidelines developed during three ERA workshops.

Lowest used Level of Concern (ppm)									
	Zooplankton, eggs, larvae			Adult Crustacea			Adult Fish		
Hour	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
0	10	5	1	50	10	5	100	50	5
3	10	5	1	50	10	5	100	50	5
24	1	1	0.5	5	2	0.5	10	2	0.5
96	1			1	1		1	1	
168	0.5	0.5		0.5	0.5		0.5	0.5	

Although the Washington ERA process was not completed at the time of this report, the other workshops arrived at their conclusions based on these data. We elected to apply these guidelines directly to probable concentrations and exposure times of concern for the Straits of Juan de Fuca dispersion scenario reviewed in this report.

Results

Surface Slick Trajectory and Impacts

The trajectory of the undispersed oil is shown in Figure 1, and a series of six panels in Figures 2a and 2b (left side). The easterly wind and ebbing tide conditions caused the oil spilled at Anacortes (at 0400) to quickly move westward through Guemes Channel and into Rosario Strait (Figure 1). Within six hours (at 1000) the center of mass of the floating oil was located in the eastern Straits of Juan de Fuca surrounding Lawson Reef, 2 nautical miles west of Deception Pass between the north end of Whidbey Island and the south end of Fidalgo Island. Examination of 95%-confidence limits indicate probable shoreline oiling during the course of this transit through Guemes Channel and in Rosario Strait (Figure 1).

(Editor's note: Figures appear at the end of this paper, following the References section.)

Left untreated, the main body of the slick stalled off Deception Pass, then began moving northwest (Figure 2a left panels.) Within 18 hours, the floating oil mass was contacting shorelines on southern Lopez Island. Over the next 12 hours it moved west also contacting the southern end of San Juan Island. Thirty hours after the spill the slick began moving to the southwest toward the center of the western basin of the Straits of Juan de Fuca. Feeding seabirds from Smith Island had a potential for oiling. From 42 to 78 hours post-spill the slick moved westward through the northern (Canadian) section of the Straits of Juan de Fuca. Our 95% confidence limits suggested that there was probability of shoreline impacts, and, presumably, oiling of sea birds, at various locations along Vancouver Island, and considerably less so on the U.S. side.

Fate and Impacts of Floating Oil

The spilled Prudhoe Bay crude oil rapidly lost volume due to evaporation, with 45-50% loss in 24 hours (Figure 3, top panel). The materials lost were the volatile, and most acutely toxic, hydrocarbons such as benzenes and toluenes. However, the floating oil also absorbed water (Figure 3, middle), forming emulsion (mousse) and nearly doubling its volume in 24 hours (Figure 3, lower panel). It also greatly increased in viscosity (not shown); if dispersion was contemplated at this point, it would be very ineffective. The net result was that while the amount of actual oil (hydrocarbons) decreased, the volume of oily product (mousse) increased substantially over the course of the spill. We did not attempt to predict the amount of oil or emulsion stranding on shorelines, or the lengths of shoreline impacted.

Inspection of Figure 3 will show that to minimize total product in, or on, the water, the optimum time to disperse the material was about three hours post-spill (0700). However, if the mousse was dispersible, at least during the first day of the spill, the optimum time to minimize the amount of dispersed hydrocarbon (oil itself, especially the acutely toxic volatiles) would be later, on the order of six to 12 hours.

Dispersed Plume

The floating oil was treated with dispersants at 1000 (6 hrs post spill) off Whidbey Island. The amount of floating oil available for treatment was 413 bbls (65,654 L). We assumed treatment was 100% successful and moved all of this volume into the water. Operationally, there would have been individual oil slicks that would have been treated within a footprint area of about 6 km^2.

The trajectory, spreading, and mean concentrations of the dispersed oil are shown in Figure 1 and the right side panels of Figures 2a and 2b. The mean and range of dispersed oil concentrations are also shown in Figure 4 (top panel), together with the plume thickness and bottom depth along the dispersed oil trajectory (bottom panel).

By the end of the first hour the dispersed oil was mixed into the upper meter of the water column, producing a mean concentration of 10.8 ppm with a range of 2.2 to 53.8 ppm (Figure 4). Over the next 6 hours (12 hours post-spill) the main body of dispersed oil mixed down to a depth of 3 m (Figure 4) and moved several kilometers southwest (Figure 2, right panels); the mean concentration of dispersed oil was 2.3 ppm (range of 0.46 to 11.4 ppm, (Figures 2 and 4). Between 6 and 18 hours after treatment (12 and 24 hours post-spill) the dispersed oil footprint(s) elongated and slowly moved southwest toward Smith Island. The dispersed oil plume would pass around Smith Island between 18 and 48 hours post dispersal (42 - 50 hours post-spill), exposing kelp beds and benthic biota to a rise and fall of dispersed oil concentrations of 0.49 (range 0.1 to 2.4 ppm) and 0.23 (range 0.05 to 1.2 ppm.) This exposure occurred between midnight and 0600. Over the next two days (post-treatment hours 24 to 72) the dispersed oil footprint moved westward into the main channel of the Straits of Juan de Fuca, with the center of mass located 5-10 km off Sequim and then Port Angeles (Figure 2) During this time mean concentrations of dispersed oil decreased another order of magnitude, from 0.23 ppm at 24 hours (west of Smith Island) to 0.03 ppm at 72 hours (north of Port Angeles but stretching westward to off Sekiu). We terminated model runs at this point because experience indicated that this water mass would continue diluting and moving seaward.

Throughout its course of travel the dispersed oil plume was over deep water (Figure 4b) and would not have contacted bottom except for parts of the plume that passed Smith Island.

Dispersed Oil Toxicity

At no time following dispersion were adult fish or crustaceans exposed to consensus guideline concentrations of high concern to the risk assessors. However, there were exceedances of consensus concentrations of medium concern for fish and crustaceans and several hours of exceedance of consensus concentrations of high concern for early life stages and zooplankton.

As shown in Figure 5, the mean concentration of dispersed oil started with a peak mean concentration (at 1 hour) of 10.8 ppm (range 2.2 to 54). The mean concentration decreased with a half life of approximately 2 hours during the first day. The consensus guideline of medium concern for adult fish, 50 ppm during the first 3 hours, was exceeded during the first hour but only by the maximum-range value of 54 ppm. During this hour the oil was mixed from the surface to 1 m. This means that there was a chance that some adult fish in the upper meter, such as herring, other forage fish or salmon, were, for less than one hour, at risk of exposure to a concentration of medium concern to the risk assessors. After the first hour there were no adult fish exposures exceeding this consensus guideline at any location. The consensus guideline of medium concern for adult crustacea (crabs, shrimp), 10 ppm during the first three hours, was exceeded by the mean plume concentration for the first hour (10.7 ppm) and by the maximum concentrations (ranging from 53.7 at hour 1 to 11.4 ppm at hour 6) for the first six hours. Over this period the oil was mixing from one to three meters deep. This means that there was a good chance that shrimp or crab in the upper several meters of the water column were, for up to six hours at risk of exposure to a concentration of medium concern to the risk managers. However, from about 6 hours onward, dispersed oil concentrations fell below this level of concern, both for the mean and maximum concentrations.

The consensus guideline of medium concern for zooplankton and early life stages of fishes and invertebrates, 5 ppm during the first three hours, was exceeded by the mean concentration during the first two hours and by the maxima concentrations during the first six hours post-treatment (Figure 5). Further, the consensus guideline of high concern for these organisms, 10 ppm during the first 3 hours, was exceeded by the mean at one hour (10.7 ppm) and the maxima for hours 1 through 6 post treatment. These observations mean that there was a good chance that zooplankton including fish and invertebrate eggs and larvae in the upper several meters of the water column were, for up to six hours at risk of exposure to concentrations of both high and medium-concern to the risk managers. Further, zooplankton exposed to maxima concentrations of dispersed oil were at risk of exceeding the consensus guidelines of medium concern to risk assessors from hours 6 to 12. However, beyond this, there were no exceedances.

Summary and Discussion

Some Ecological Tradeoffs

Dispersing 413 bbls of 6-hour, weathered crude oil off Whidbey Island initially resulted in a several-square-kilometer patch of upper, mixed-layer water containing concentrations of oil in the range of 10 to 50 ppm, declining to a range of .5 to 5 ppm during the first day or so. Based on collective consensus guidelines, these concentrations and exposure times would be of medium to high concern to risk assessors with respect to plankton, fish eggs, and fish larvae within the plume, but of much less concern with respect to adult crustaceans. Adult fish were at risk of medium concern only during the first hour.

If dispersion was 100% effective, shorelines of the San Juan Islands and Vancouver Island, and resident feeding shorebirds, would have been spared oiling and the main body of dispersed oil would be almost entirely in U.S. waters.

Undispersed, and otherwise untreated, the floating oil would have continued to disperse slightly, emulsify, increase in volume, and increase in viscosity, making open-water mechanical recovery difficult and subsequent dispersion or burning nearly impossible. Seabirds foraging from Lopez, San Juan, Smith, and Vancouver islands would have been oiled and subject to capture and rehabilitation. We did not estimate the amount of oil or emulsion stranding on shorelines, lengths of shoreline impacted, or numbers and kinds of seabirds at risk from oiling, but that should be done. However, we can point out that the material stranding on shorelines of the southern San Juan Islands would be emulsion (mousse): it would have come ashore as brown sticky mats, stranding along the high tide line on sand and gravel beaches. This could put the spawn of sand lance (*Ammodytes hexapterus*) and surf smelt (*Hypomesus pretiosus*) at risk. If the day was warm and sunny, the stranded mousse would become less viscous, and then penetrate into the sand and gravel: residual oil would remain in the gravel after manual cleanup unless moved by front-end loaders for berm-relocation or by surf washing. Such methods would also damage the eggs of shore spawning fishes and also, ironically, disperse oil into the very shallow nearshore zone occupied by algae, seagrasses, crabs, and juvenile fishes such as Pacific herring (*Clupea harengus harengus*). Residual oil might be present for years.

The ecological and fisheries tradeoffs seem clear: on one hand, dispersion may injure or kill plankton and early life stages of fish in a several square-kilometer patch of water during part or all of the first day. Alternatively, not dispersing or otherwise removing surface oil would oil seabirds and cause short- and long-term oiling of shorelines occupied by shorebirds and possibly by the spawn of forage fishes.

Limitations, Reality Checks, and Recommendations

For this scenario we did not attempt to simulate alternate responses alternatives such as mechanical removal. That was done in California and Texas (Aurand and others 2001). Traditional methods are indeed effective in calm water, but much less so in chop and the fast-moving tidal currents common in this particular area.

The consensus guidelines offered by ERA workshop facilitators and participants (Table 3) represent a major step forward in making effective use of existing and new toxicity data: however, we urge that these guidelines be revisited and further reviewed as new data become available. We did not account for biological responses other than toxicity. For example, adult fish, such as salmon, were probably at no toxicity risk because they are capable of detecting and avoiding dispersed oil (Green and others 1982; Nakatani and Nevissi 1991). Alternatively, shellfish, such as oysters and clams, are capable of temporarily bioaccumulating (and then depurating) dispersed oil (Michel and Henry 1997), a factor that could lead to temporary closure shellfish harvesting.

The scenarios and workshop proceedings were based on *modeling*, not on actual spills. Experiences dispersing real spills have occurred in Europe, such as at the large nearshore *Sea Empress* spill in Wales (Lunel 1998). There have been numerous sea trials in the North Sea and these have been used to test dispersion technology, providing new data for resolving uncertainties in models (Lunel and Davies 1997) and clearer guidance on dispersant operations (Lunel and Lewis 1999). Based on this and other at-sea experiences, we believe our dispersion simulation is extremely conservative, producing oil concentrations that may be too high and too long lasting compared to what may actually happen. The model results need to be confirmed in the real world.

This and other scenarios may be overly optimistic in terms of the effectiveness of dispersant operations and the scales and amounts of oil that can actually be dispersed. In the real world, dispersion will not be 100% effective—some oil will remain untreated or unresponsive.

This review did not account for studies concerning the long-term fate of dispersed oil (including comparison with those of alternative responses). Enhanced biodegradation via the microbial and planktonic food web is a distinct possibility (Swannel and Fabian 1999). We are continuing to review existing literature on long-term monitoring of ecosystem effects following dispersed oil spills and on the extent to which benthic and other nearshore resources respond to and recover from such exposure.

The goal of this and similar ERA efforts in California and Texas was to acquaint fish and wildlife resource managers with comparative benefits and hazards of dispersing oil in nearshore area. Simulation models were extremely useful. We do not present the final process here and refer interested readers to workshop reports such as Pond et al. (2000).

There is great need of good monitoring data both in terms of effectiveness and effects of dispersant operations. A modified fluorimetry system and protocol is available and in use by the Coast Guard for rapid response monitoring of dispersion effectiveness (Henry and others 1999) and use of this coupled with pertinent observations (Levine 1999), and with modeling (such as done here), would provide valuable new information and allow for better planning simulations.

The final judgment on pre-approval requires input from the political and public process. Short of pre-approving dispersant use, we urge managers and responders to at least consider dispersion as an option during future spills, call for modeling if appropriate, and at least include dispersion as an option in future spill drills.

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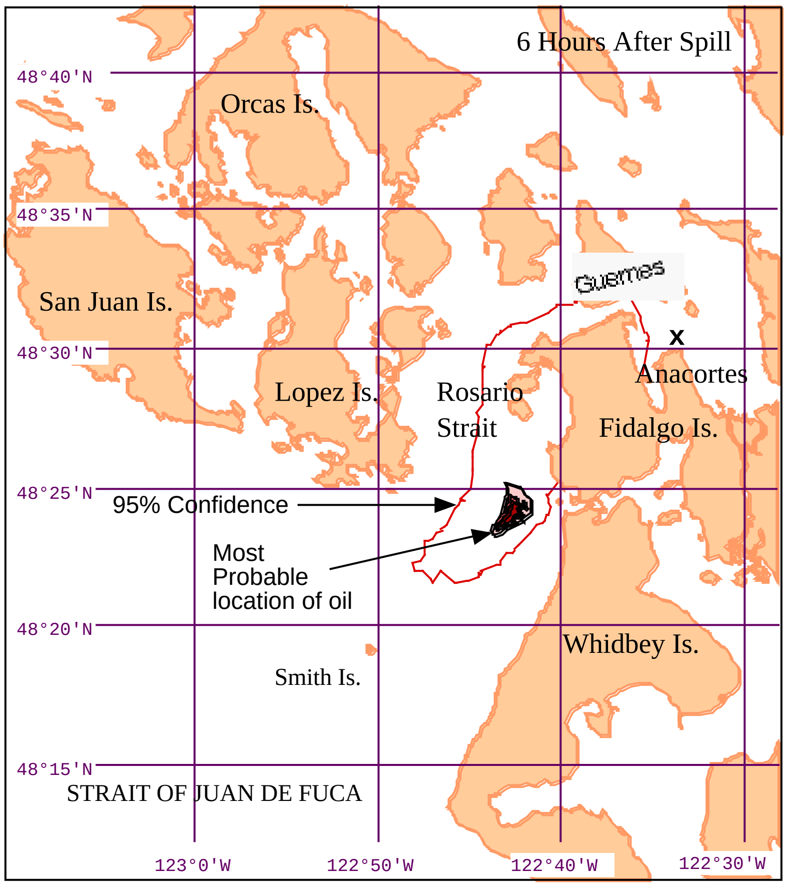

Figure 1 Location and size of 500 bbl crude oil spill slick at 1000 h, 6 hours after release at Anacortes (X) during an ebb tide, just before dispersal. Trajectories of dispersed and undispersed oil follow in Figure 2.

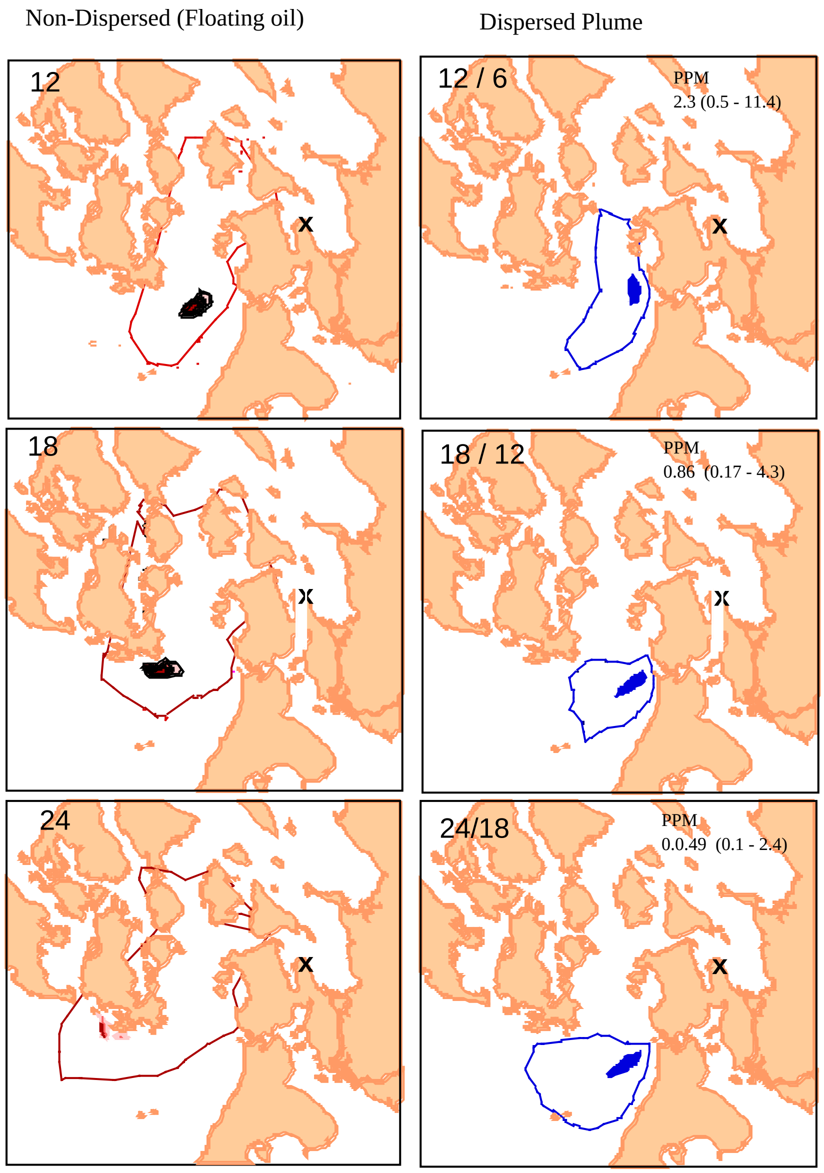

Figure 2a. Six- and 12-hourly snapshots of the locations of undispersed oil slick and dispersed oil plume footprints, and 95% confidence limits, for a spill of 500 bbls of PBCO crude oil on ebb tide off Anacortes, Washington. Hours after spill/after dispersal shown in upper left corner; mean and range of expected plume oil concentrations shown in upper right. Continued in Figure 2b.

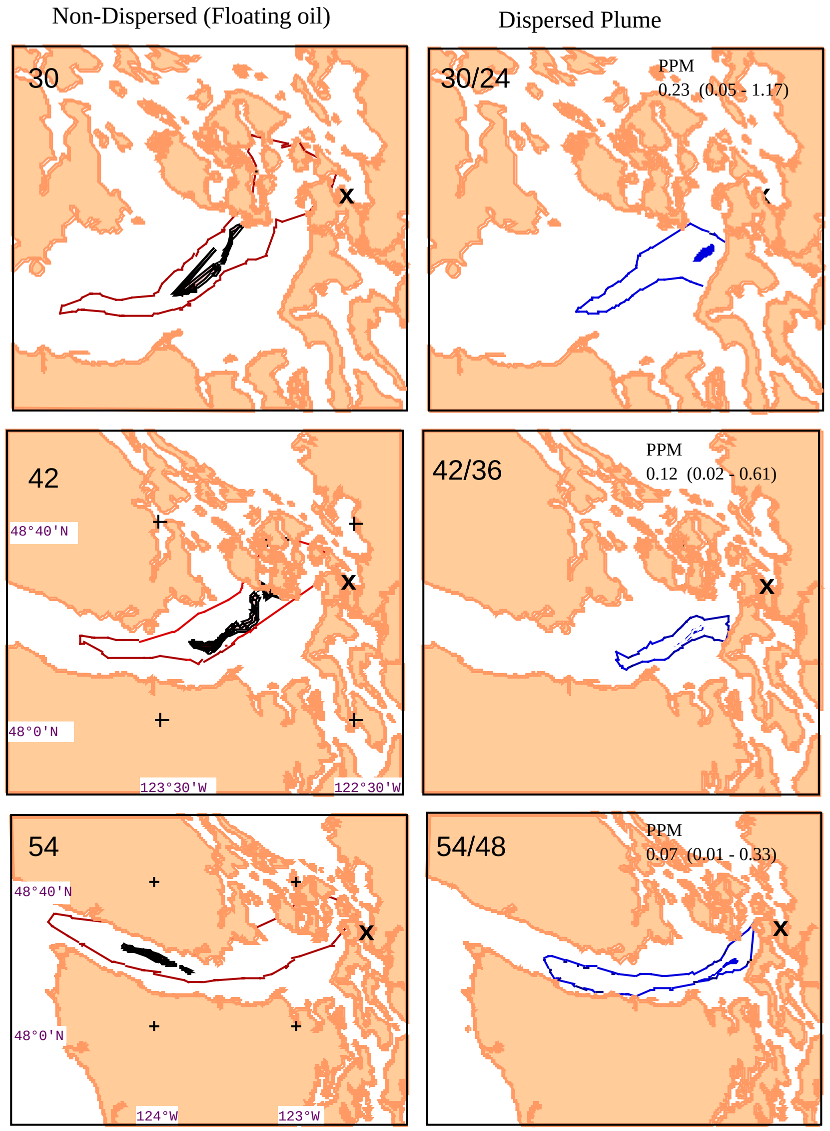

Figure 2b 12- and 24-hourly snapshots of the locations of undispersed oil slick and dispersed oil plume footprints, and 95% confidence limits, for a spill of 500 bbls of PBCO crude oil on ebb tide off Anacortes, Washington. Hours after spill/after dispersal shown in upper left corner; mean and range of expected plume oil concentrations shown in upper right. Continued from Figure 2a.

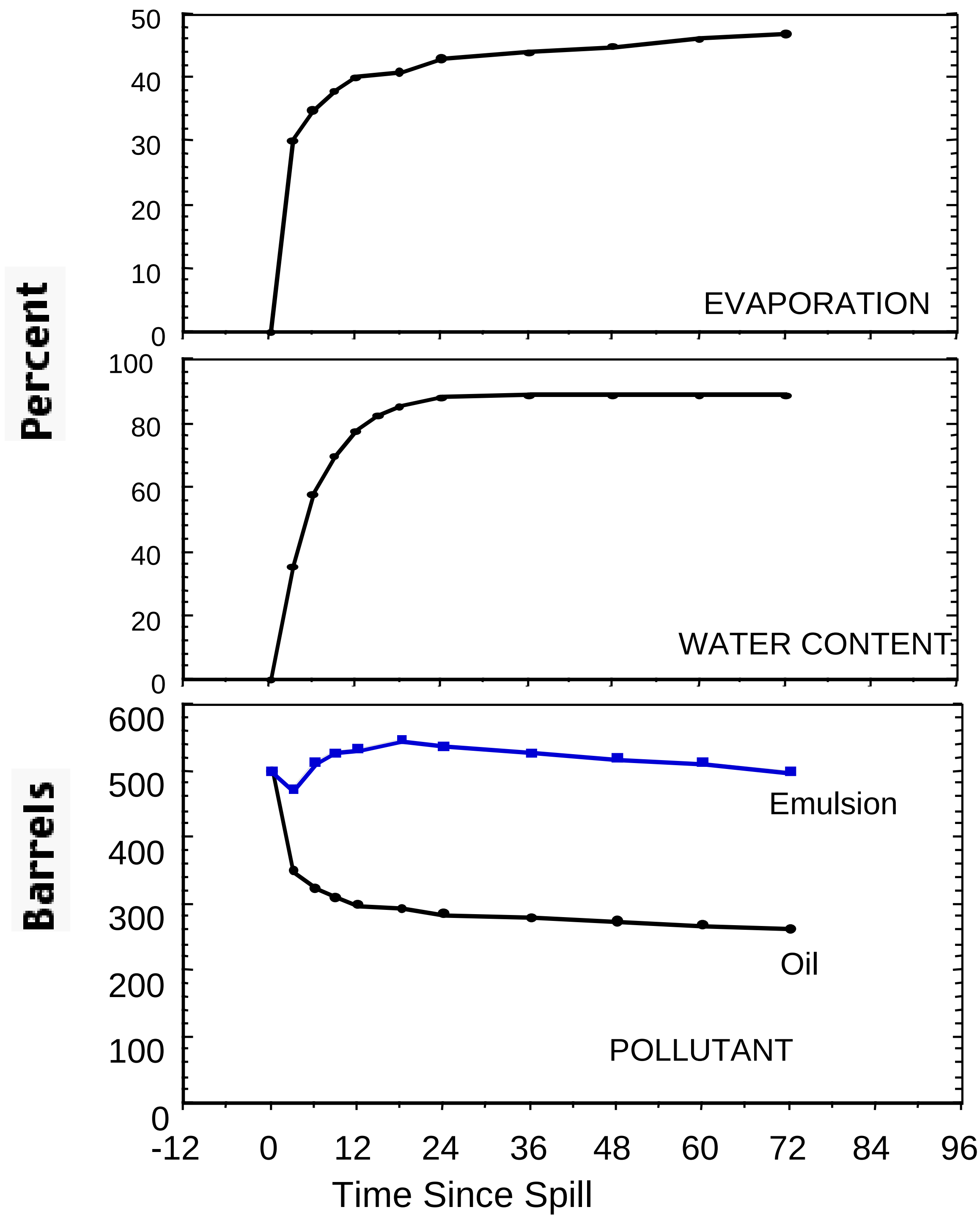

Figure 3 Weathering of 500 bbls of Prudhoe Bay Crude Oil: fraction oil evaporated (top panel), remaining oil water content (middle panel) and volumes of emulsion (mousse) and floating oil.

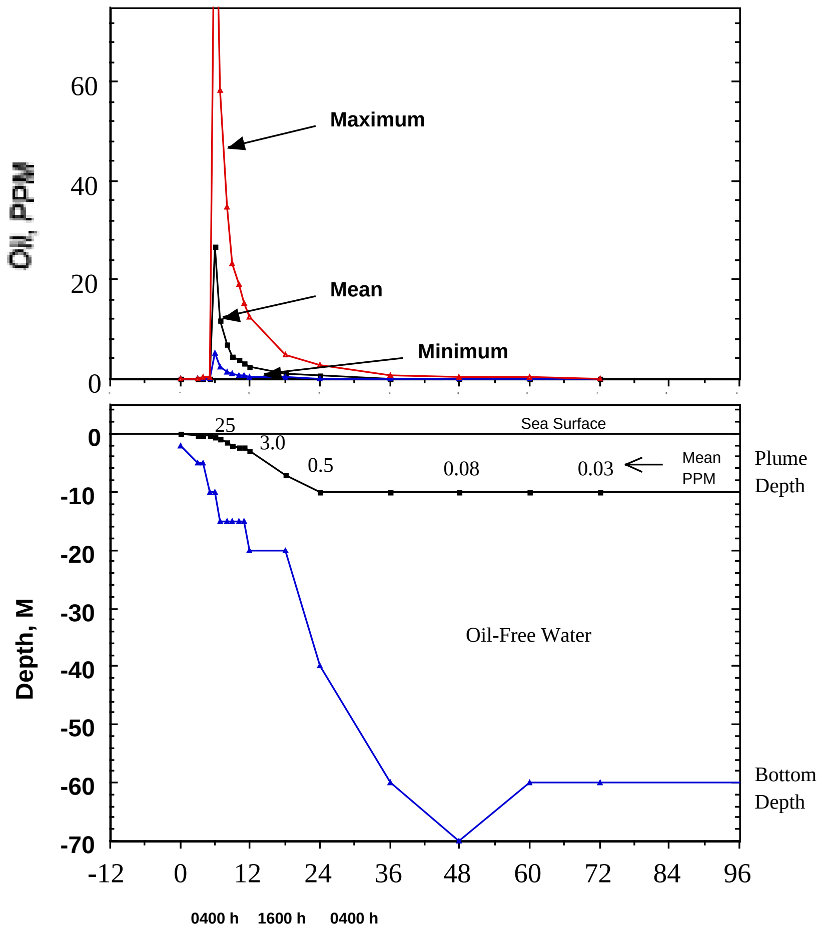

Figure 4 Comparison of mean, maximum and minimum dispersed oil concentration time series (upper panel) with dispersed plume depth and bottom depth along the plume trajectory (bottom panel). Mean, minimum and maximum concentrations shown in upper panel. Based on dispersal of 413 bbls Prudhoe Bay crude oil off Whidbey Island, Washington (see Figure 1).

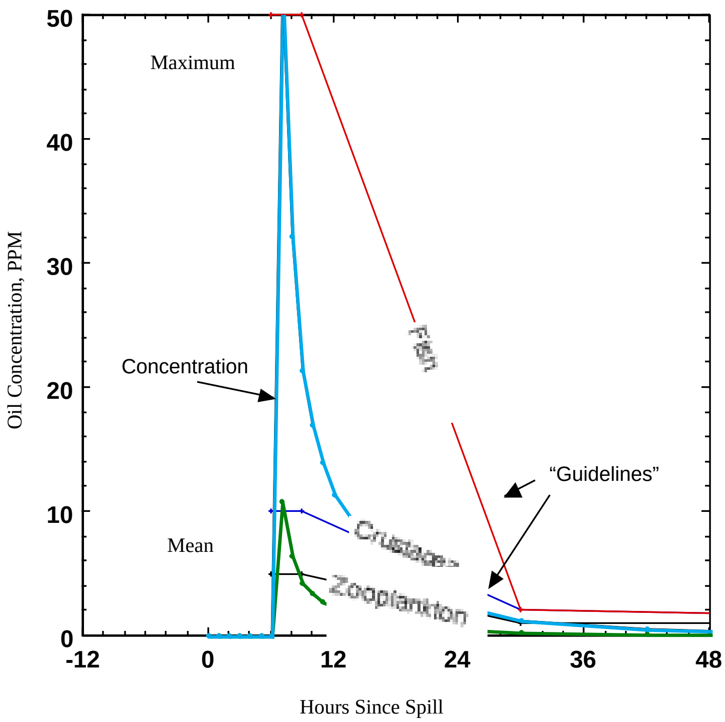

Figure 5 Comparison of Anacortes dispersed oil spill maximum and mean concentrations with consensus concentrations of medium concern for adult fish, adult crustacea and zooplankton/early life fish stages. Consensus guideline concentration for 3 hours, 24 hours and 96 hours are connected by dashed lines.